IN THE UNITED STATES PATENT AND TRADEMARK OFFICE
APPLICATION FOR LETTERS PATENT
(UTILITY PATENT)

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INVENTION TITLE: MULTI-MODAL RF COIL FOR MAGNETIC RESONANCE
                       IMAGING

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Sir:

       Your applicant(s) named above hereby petition(s) for grant of a utility patent to him (them) or any assignee(s) of record, at the time of issuance, for an invention, more particularly described in the following specification and claims, with the accompanying drawings, verified by the accompanying Declaration and entitled:

Multi-Modal RF Coil For Magnetic Resonance Imaging

Cross Reference to Related Applications

[0001]   This application is a continuation-in-part of pending U.S. Patent Application No. 10/766,049 entitled "Multi-Modal RF Coil For Magnetic Resonance Imaging", filed January 28, 2004, said application being incorporated herein by reference.

Field Of The Invention

[0002]   This invention relates generally to magnetic resonance imaging RF coils, and, more particularly, to the imaging of an anatomical region of interest, such as the human female breast, for the purpose of early detection of cancerous growths and lesions.

Background Of The Invention

[0003]   In the US alone, breast cancer is the second leading cause of female cancer mortality. Each year breast cancer strikes more than 200,000 US women and results in the deaths of approximately 40,000. Early detection is the key to saving lives and reducing the cost of treating breast cancer. The American Cancer Society reports that 96% of all women survive breast cancer when it is detected in its early stages; however, one in four is unlikely to survive with late detection (1). The average cost of treating early breast cancer today is estimated to be between $10,000 and $15,000, while late stage treatments average more than $100,000. Magnetic resonance imaging (MRI) is a widely used clinical soft-tissue diagnosis tool that has enjoyed significant success. However, commercially available whole-body imaging systems with large encircling coils are less efficient when the goal is to obtain detailed, high-resolution images from a localized area such as the female breast. Researchers have recognized these limitations and have developed a number of specialized designs, mostly related to breast-encircling coils, such as illustrated generically in **Figure 1**. A good example of the present state-of-the-art in RF coil development is encapsulated in the patent US 6,023,166 (Feb. 8, 2000) issued to Greg Eydelman of Fonar Corporation. Eydelman built a

system consisting of a primary RF coil encircling the entire human chest and two secondary (two winding) RF coils fitted over each breast.

[0004] Additional single loop (US 5,646,530, Diagnostic Instruments, July 8, 1997) or array coil (US 6,493,572, Toshiba, Dec. 10, 2002) configurations have been proposed. Particularly the array coil concept attempts to capitalize on the use of multiple receiver channels to improve signal-to-noise ratio. Unfortunately, these multi-loop coil configurations are less efficient due to their fixed wire arrangement; they typically cover only a small region of interest (ROI) in the center of the breast and leave critical areas near the breast bone insufficiently covered.

[0005] There exists, therefore, a need to provide an anatomically shaped coil that covers the entire extent of a ROI, such as a breast volume, which is better suited to detect the early onset of cancer, for instance by being more sensitive to the increased water content associated with malignancy. A high signal-to-noise ratio (SNR) RF coil may provide sufficient sensitivity to yield a detectable response in localized increases in blood volume present during angiogenic activity observed in early tumor growth.

Summary Of The Invention

[0006] The needs for the invention set forth above as well as further and other needs and advantages of the present invention are achieved by the embodiments of the invention described hereinbelow.

[0007] The present invention is directed to a single or dual set of multi-modal radio frequency (RF) coils for use in a magnetic resonance (MR) imaging system. Each RF coil is dimensioned so as to receive an anatomical region of interest to be imaged, such as a human breast. Each RF coil functions in at least two modes operated in phase quadrature. In a RF quadrature detection configuration, pairs of MR signals are processed and combined to obtain one combined MR signal having a better signal-to-noise ratio than either of the single signals from the individual RF coil channels of the configuration.

[0008]   In one embodiment, the RF coil is comprised of a segmented annular base ring conductor, a plurality of capacitive electrical connections (*e.g.*, fixed and/or tunable capacitors) disposed between the segments of the base ring, and at least one arcuate conducting strap having one end in direct electrical contact with the base ring and another end electrically connected to the base ring through two of the capacitive electrical connections (*e.g.*, one or more fixed and/or tunable capacitors.) The ends of each strap terminate at spatially distinct positions along the base ring, symmetrically disposed with respect to an imaginary central axis of the base ring. Some of the capacitances employed may serve to tune the RF coil to a desired resonance frequency and/or match the coil's impedance to one or more transmission lines for interfacing the coil with the single- or multi-channel receiver electronics of the MR instrument with which the RF coil is utilized.

[0009]   The term "arcuate" as used herein, encompasses a variety of geometrical shapes having appropriate dimensions to receive the anatomical region of interest. Any suitable conductor may be used in forming segments of the base ring and strap, but preferably microstrip lines are employed.

[00010]   In alternative embodiments described below, a single strap or multiple straps are operated in multiple receiving (or transmitting) modes in order to establish a rotating magnetic field phasor orthogonal to the main magnetic field created by the MR instrument in which the RF coil is utilized.

[0010]   In a single-strap embodiment of the RF coil, a first of two modes is established by current flowing circularly through the annular base ring, and a second mode is established by a 90° phase shifted current flowing through the strap and evenly branching between two halves of the annular base ring. Each strap is preferably composed of multiple conductor segments electrically connected to one another by capacitive electrical connections (*e.g.*, one or more fixed and/or tunable capacitors) whose reactances compensate the coil's inherent inductive reactance at a resonant frequency. These capacitances also serve to reduce eddy currents induced in the conductors by the switching gradient field.

[0011]   As described below, electrical ports of the RF coil may be configured to interface with a plurality of standard transmission lines (*i.e.*, coaxial cables) for conveying signals to a single or multi-channel receiver amplifier of the MR instrument, or may be adapted with hybridizing components to reduce the number of transmission lines required to achieve the interface.

[0012]   In another embodiment of the present invention, two multi-modal RF coils are disposed with their respective segmented annular base rings so as to enable simultaneous imaging of two anatomical regions, such as two breasts of a patient.

Brief Description Of The Figures of the Drawing

[0013]   For a better understanding of the present invention, together with other and further objects thereof, reference is made to the accompanying drawing and detailed description, wherein:

Figure 1 is an illustration of a prior art RF coil configured for pendant use in magnetic resonance imaging of a human breast;

Figure 2 is a side view illustration of a generic cup-shaped RF coil positioned proximate a female breast;

Figure 3 is an illustration of a single-strap RF cup-coil showing the approximate, relative positioning of electrical components thereof;

Figures 4A, 4B are illustrations of single-strap embodiments of the RF cup-coil indicating two modes ($Mode_0$, $Mode_1$) of operation possible for magnetic resonance imaging;

Figure 4C is an illustration of the combined magnetic field vector B_{RF} produced by the individual magnetic fields associated with $Mode_0$ and $Mode_1$;

Figure 5 is an illustration of a three-strap embodiment of the RF cup-coil of the present invention;

Figure 6A is a schematic of the equivalent electronic circuit of the single-strap RF cup-coil;

Figure 6B is a schematic of the equivalent electronic circuit of the single-strap RF cup-coil populated with standard capacitors;

Figure 7A is a graphical plot of the magnitude of the reflection coefficient versus frequency showing the resonances associated with $Mode_0$ and $Mode_1$ in an untuned state;

Figure 7B is a graphical plot of the magnitude of the reflection coefficient versus frequency showing $Mode_0$ and $Mode_1$ combined and tuned to 63.87 MHz, ;

Figure 8 is a schematic circuit diagram illustrating electrical components utilized in an optional RF coil interface circuit for dual-mode coils; and

Figure 9 is an illustration of a dual coil, single-strap RF coil configuration equipped with shielding disposed between the coils.

Detailed Description of Preferred Embodiments of The Invention

[0014] With reference to **Figure 2**, the present invention is directed to a single or dual set of radio frequency (RF) cup-coils **2** configured to receive an anatomical region of interest, such as human breast(s) **4**, and to function in at least two receiving modes operated in quadrature configurations. The cup-coil **2** is illustrated in an pendant configuration within the bore **9** of a conventional MRI scanner, but the cup-coil can also be operated in a vertical position. The principles of operation of conventional MRI systems are well understood. (see, for example, U.S. Patent No. 5,363,845 incorporated herein by reference) Generally speaking, a static uniform magnetic field B_0 **8** is applied to an object to be imaged to align the object's nuclear spins along the direction of the magnetic field B_0. Then so-called gradient coils **7** arranged cylindrically with respect to the static uniform field generate a magnetic field gradient that allows spatial slice selection. An RF coil tuned to the resonance frequency of the nuclei in the slice, upon being driven by a transmit signal, allows for reorientation of the nuclei. The same RF coil, or a special receive coil, subsequently records the relaxation process of the nuclei. The processing of multiple receive signals results in the formation of an image of the particular slice of the anatomical region.

[0015] **Figure 3** schematically illustrates a single-strap embodiment of a RF cup-coil **2**, wherein an arcuate strap **10** is connected to a base ring **12** and passes through an imaginary central axis **18** of the base ring **12**. As noted above, the term "arcuate" is meant to encompass non-hemispherical shapes such as, for example, rectangles, ellipses, parabolas, or other shapes. Strap **10** is directly connected to base ring **12** at one end at point C **20**, and electrically connected to base ring **12** through tuning capacitors C_{MA}, C_{MB} **14** bridging the gaps **26** between its other end (point D **22**) and two segments of base ring **12**. The strap **10** and base ring **12** can be implemented with microstrip conductor lines (*e.g.*, copper) or any other conducting material, and are dimensioned so as to receive the anatomical region of interest (*e.g.*, a human breast.) The capacitors C_A, C_B, C_C **16** and the inherent inductances L_1, L_2, L_3 of the segments of microstrip lines form a resonance system that can be tuned to a particular

resonance frequency based on the requirement of the main magnet system of the magnetic resonance (MR) instrument. In order to tune the cup-coil **2** efficiently, fixed and tunable capacitors C_A, C_B, C_C **16** are deployed at strategically selected cuts **24** in the microstrip segments comprising strap **10** and base ring **12**. The selection and adjustment of tuning capacitors C_{MA}, C_{MB} **14** is based upon the resonance requirement of the cup-coil at a desired frequency. For instance, the capacitors C_{MA}, C_{MB} **14** can be adjusted such that a resonance frequency of 63.87MHz is achieved, consistent with a 1.5T main magnetic field of a MR system for proton imaging. Other magnetic field strengths can be implemented, such as 3T and higher. Capacitors C_A, C_B, C_C **16** can be selected and/or adjusted such that their reactances compensate the inherent inductive reactances of the cup coil the cup-coil **2**, and such that together with the microstrip inductances L_1, L_2, and L_3, the desired resonance frequency is obtained. They also reduce eddy currents that would result as a consequence of the switching gradients of the MR system. The reactance associated with capacitor C_3 should be chosen such that it compensates for the inductance associated the inductance L_3 of the upper strap.

[0016]   **Figures 4A** and **4B** illustrate, respectively, the two modes ($Mode_0$, $Mode_1$) of operation available in the single-strap RF cup-coil **2** and the magnetic fields associated therewith. In $Mode_0$, no current flows through strap **10** while a current I **26** induced in the base ring **12** by the magnetic flux density travels around the annular base ring **12** along current path A-C-B-D. In $Mode_1$, a 90° phase shifted current 2I **30** is induced in the strap **10** and is divided symmetrically into two currents I **32** between two halves of the base ring **12** (or vice versa) along current paths D-A-C and D-B-C respectively. The superposition of the modes establishes a rotating magnetic field phasor B_{RF} **6** (shown in **Figure 4C**) orthogonal to the uniform static uniform field B_0 **8** (shown in **Figure 2**) of the MR instrument.

[0017]   In alternative embodiments, multiple straps may be employed for a greater number of operating modes. For example, **Figure 5** illustrates a three-strap, six-port, embodiment **34** of the RF cup-coil that encompasses a higher number than two operating modes, and enables

thus more controlled coverage in comparison to the single-strap embodiment. In multi-strap embodiments, each strap **36** is substantially parallel to and spaced-apart from each other's strap by a fixed distance **38**, symmetrically disposed with respect to the central axis **18** of the base ring **12**. Although not depicted for simplicity, each strap **36** is connected to the base ring conductor **12** as is the strap in the single-strap embodiment, *i.e.*, directly on one end and electrically through a bridging capacitor on the other. Additionally, each strap **36** is comprised of multiple, electrically connected segments of conductors, preferably microstrip lines. The capacitors disposed in the gaps between the conductor segments comprising each strap **36** must similarly be selected to create resonance conditions with the inductance of that strap.

[0018]   **Figure 6A** presents an electronic equivalent circuit **40** of the single-strap RF cup coil **2** depicted in **Figure 3**. Nodes A-D in circuit **40** correspond to the identically labeled points in the schematic model of the cup-coil **2** shown in **Figure 3**. Electrical losses in the cup-coil **2** are represented in the model circuit by resistors R_1 through R_3. The operational and dimensional specifications of a single-strap RF cup-coil implemented using standard fixed and variable capacitors on a dielectric "former" are reflected in **Figure 6B** and in **Table One** and **Table Two**. Specifically, the resonance of 63.87MHz was selected to be compatible with the static field strength of a 1.5T magnetic resonance system for proton imaging. However, by changing the coil geometry and the lumped element capacitor values, other frequencies corresponding to higher field strengths, such as 3 and 4T, can readily be realized. The quality factor, as a division of the magnetic resonance frequency over the 3 dB bandwidth, is recorded for an empty or unloaded coil and can deviate from the listed number by a wide margin depending on losses associated with the deployed capacitors and former materials among other factors. Those skilled in the art will readily appreciate that the details provided are in no sense limiting, as the operational characteristics are easily changed to accommodate the anatomical region of interest to be imaged and/or the resonance frequency desired. For

example, the coil diameter has been increased to 250mm in other implementations of the cup-coil.

Capacitor Value	Manufacturer	Part No.
1-40 pF trimmer	Voltronics	NMP40M
10 pF (± 5%)	Voltronics	V205 100J
47 pF (± 5%)	Voltronics	V205 470J
100 pF (± 5%)	Voltronics	V205 200

Table One

Parameter	Values
Coil diameter	200.0 mm
Coil Width (strip width)	40.0 mm
Former outer diameter	200.0 mm
Former inner diameter	187.3 mm
Former material	cast acrylic
Former height	40.0 mm
Thickness copper strips	38 μm
Operating frequency	63.87 Mhz
Quality Factor (unloaded Q)	158.35
3 dB bandwidth	0.40 MHz

Table Two

[0019]   Additional cup-coil design choices that may optimize the signal-to-noise ratio and homogeneity include the number of straps employed, the length and shape of the strap(s) (alternate shapes, such as, for example more rectangular geometries, are deemed to fall within the definition of the term "arcuate" as used herein), and the dimensions of the base ring. The values of the capacitors in the example were selected based upon the values of the calculated inductances L_1, L_2, L_3 and the desired operating frequency of 63.87 Mhz. The magnitude of the reflection coefficient S11 versus frequency shown in **Figure 7A** (recorded with a HP 8345 network analyzer) demonstrates that an untuned single-strap RF coil **2** includes two modes **42, 44**. **Figure 7B** demonstrates that the cup coil **2** can be tuned and matched to a selected resonance frequency **46**. Through appropriate selection of capacitor values C_A, C_B, C_C **16**, different resonance frequencies can be achieved.

[0020]   With reference to **Figure 8**, the cup-coil **2** may be interfaced through standard cabling and a single or multi-channel receiver amplifier to existing clinical MR instruments, such as manufactured by GE, SIEMENS, TOSHIBA, and others. The induced receiver current may be picked up by two standard coaxial cables (not shown) at ports **48** and **50** formed at the gaps **26** between strap **10** and base ring **12**. Tuning capacitors C_{MA}, C_{MB} **14** and one or more matching capacitors match the cup-coil impedance to the desired transmission cable impedance(s) (*e.g.*, 50 Ω.) Alternatively, the induced currents picked up at ports **48, 50** can be adapted for a single transmission line interface by combination with a 180° quadrature hybrid **52**, two optional pre-amplifiers **52**, and a 90° quadrature hybrid **56**.

[0021]   With reference to **Figure 9**, two RF cup-coils **2** may be used and arranged with their respective base rings **12** in order to simultaneously image both breasts of a patient. Mutual electromagnetic interference between the coils **2** may be minimized by positioning segmented conductive foil as shielding **54** between them, or by carefully controlling the operational timing of the coils. Furthermore, interference between conventional RF transmitter coils and the single or dual RF cup-coil **2** can be minimized by employing an active tune, de-tune circuit (not shown.) Specifically, so-called PIN diodes can be connected in shunt with one or multiple capacitors of the cup-shaped coil. These PIN diodes receive a static bias voltage signal such that when biased in reverse direction, a high ohmic state exists at resonance, *i.e.*, the PIN diodes do not affect the operation of the RF cup-coil(s). However, if the static bias voltage signal is applied in forward direction, a low ohmic state exists at resonance, *i.e.*, the PIN diodes provide a low impedance bypass of the associated capacitors, thereby shifting the RF coil's frequency away from the original resonance frequency. As a result, during transmission of RF energy into the biological load, the RF coil will not cause undesired interference. Additional quadrature hybrid combiners are optionally employed to interface both RF coils to a single-channel receiver amplifier.

[0022]   Although the invention has been described with respect to various embodiments, it should be realized that this invention is also capable of a wide variety of further and other embodiments within the spirit and scope of the appended claims.

[0023]   We claim: